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Optimization in ultrasonic imaging systems: Use of metaheuristics to design sparse arrays and a heuristic to create an acquisiton system

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TÍTULO DA TESE: Optimization in ultrasonic imaging systems: use of metaheuristics to design sparse arrays and a heuristic to create an acquisition system

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"I have not failed. I have found 10,000 ways that it will not work"

Thomas Edison

RESUMO

Imagens ultrassônicas possuem importante papel no diagnóstico médico e ensaio não destrutivo. Uma das alternativas para geração de imagens consiste em utilizar um *array*, um transdutor composto por um conjunto de elementos piezelétricos, para gerar diversas frentes de ondas e amostrar suas reflexões. Uma característica física importante para construção dos *arrays* é a sua dimensão. Quanto maior a extensão do *array*, melhor será a resolução lateral da imagem gerada. Além disso, uma recomendação de fabricação dos *arrays* é que o centro do seus elementos precisam estar espaçados por uma distância (*pitch*) menor ou igual a $0,5\lambda$, em que λ é o comprimento da onda gerada pelo transdutor. Desta forma, as imagens geradas por esses *arrays* não apresentam artefatos causados pelos lóbulos de espaçamento. A recomendação para o uso de *arrays* é que seja o maior *array* possível, respeitando a restrição de *pitch*. No entanto, o volume de dados, recursos e custo de fabricação aumentam proporcionalmente à medida que o número de elementos no *array* aumenta, o que pode torná-lo impraticável dependendo da aplicação. Esta tese propõe técnicas para reduzir o uso de recursos em sistemas ultrassônicos visando obter imagens com alta resolução lateral e mitigar eventuais desvantagens. No primeiro estágio, *arrays* esparsos lineares cujos *pitches* são superiores que $0,5\lambda$ são estudados. Propõe-se uma nova estratégia para projetar esses *arrays*, na qual é apresentada uma nova codificação matemática para os *arrays* esparsos e uma função de aptidão baseada na equação de energia e entropia das PSFs (*Point Spread Function*). Posteriormente, algoritmos de otimização estocástico são utilizados para desenhar as configurações esparsas lineares. A função aptidão proposta foi comparada com a função aptidão mais utilizada na literatura, baseada no diagrama de radiação. Identificou-se que a função proposta valoriza configurações de *arrays* esparsos que geram imagens com melhor equilíbrio entre contraste e resolução lateral. Além disso, foi identificado que a função aptidão proposta na literatura apresenta inconsistências ao avaliar os *arrays* esparsos, o que não ocorre na função proposta. Em seguida, uma nova estratégia de aquisição de dados para *arrays* bidimensionais que não estão em uma malha é proposta. A estratégia se baseia em analisar as projeções dos elementos do *coarray* e manter somente as combinações de elementos emissores e receptores mais importantes para a geração de imagens. Assim, o número de aquisições e volume de dados de aberturas esparsas bidimensionais, cujos elementos não estão posicionados em uma malha, é reduzido, bem como o tempo de geração de imagens. As análises dos resultados indicaram a viabilidade em reduzir os sinais adquiridos sem comprometer a qualidade das imagens geradas. Adicionalmente, foram desenvolvidas duas figuras de mérito baseadas na análise da disposição espacial dos elementos, que por sua vez foram utilizadas para avaliar *arrays* 2D esparsos. A relação entre as figuras de mérito desenvolvidas e a energia irradiada pelos *arrays* foi estudada e, a partir desta análise, uma função custo desenvolvida. Em seguida, é apresentada uma estratégia para projetar *arrays* 2D esparsos utilizando o algoritmo *simulated annealing*. As análises do diagrama de radiação das aberturas bidimensionais esparsas obtidas pelo algoritmo de busca possuem características desejáveis com alta resolução lateral e baixa intensidade nos artefatos. A tese possui três contribuições para os sistemas de geração de imagens por ultrassom que reduzem os custos de manufatura e computacional.

Palavras-chave: Algoritmos de Otimização Estocástico. *Arrays* 2D Esparsos. *Array* Lineares Esparsos. Metaheurísticas.

ABSTRACT

Ultrasonic images have an important contribution to medical diagnosis and non-destructive testing. One strategy to generate an image is to use an array, which is a transducer composed of a set of piezoelectric elements, that emits several wavefronts and samples the reflected waves. An important physical characteristic of arrays is their dimension. The wider the array extension, the better the lateral resolution of the generated image will be. Additionally, a construction recommendation for arrays is that the centre of their elements must be spaced by a distance (pitch) less or equal to 0.5λ, where λ is the generated wavelength by the transducer. Thus, the images generated by these arrays do not present artefacts caused by the grating lobes. The recommendation for using arrays is that it has to be the wider array possible, respecting the pitch recommendation. However, the data volume, resource, and manufacturing cost proportionally increase as the number of elements in the array rises, which might be impractical to use this array depending on the application. This thesis investigates techniques to reduce the use of resources in ultrasonic systems aiming to achieve images with high lateral resolution and mitigate any disadvantages. In the first part of this thesis, the linear sparse arrays, which are arrays that pitch higher than 0.5λ are studied. A new strategy to design these arrays is proposed, where a new mathematical codification for sparse arrays and fitness function based on the equation of energy and entropy of the PSFs (Point Spread Function) are presented. Subsequently, stochastic optimization algorithms are used to design sparse configurations. The proposed fitness function was compared with the most used fitness function in the literature based on the radiation pattern. The sparse arrays found using the proposed fitness function generated images with a balance between contrast and lateral resolution. Moreover, it was noticed that the fitness function proposed in the literature has inconsistencies when evaluating sparse array configurations which do not happen with the proposed fitness function. Next, a new data acquisition strategy for synthetic aperture for two-dimensional arrays that are not in a grid is proposed. This strategy is based on analysing the projections of the elements of the coarray and keeping only the combinations of emitter and receiver elements that are most important for image generation. Consequently, the number of acquisitions and data volume of sparse two-dimensional apertures, whose elements are not positioned in a grid, is reduced, as well as the image generation time. The results indicate that it is possible to reduce the number of acquiring signals without compromising the quality of the ultrasonic image generated. In addition, two figures of merit based on the spatial distribution of the elements were used to evaluate sparse 2D arrays. A study of these parameters and how they influence the energy irradiated by arrays is done, and a fitness function is created. Then, a strategy to design a sparse 2D array is proposed using the simulated annealing algorithm. The radiation pattern analysis of the sparse arrays obtained from the search algorithm shown that the aperture generated images with high lateral resolution and low artefact intensities. The radiation pattern analysis of the sparse arrays obtained from the search algorithm showed that the aperture generated images with high lateral resolution and low artefact intensities. This thesis has three main contributions to ultrasonic systems that reduce manufacturing and computational costs.

Keywords: 2D Sparse Arrays. Linear Sparse Arrays. Metaheuristics. Stochastic Optimization Algorithms.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACQ	Acquisition strategy
AOA	Arithmetic optimization algorithm
bPSO	binary particle swarm algorithm
CP	Crossing Point between lateral profiles
CNR	Contrast to noise ratio
CPG	Coarray Projection Grid
DTFT	Discrete-Time Fourier transform
DR	Dynamic range
FF	Fitness function
FMC	Full matrix capture
FPA	Fully populated array
GFP	Global Free Positions
GNFP	Global Non-Gree Positions
GA	Genetic algorithm
GPGPU	General-Purpose Graphics Processing Units
ICPG	Inverse Coarray Projection Grid
MLW	Main-lobe width
MRC	Minimum redundancy coarray
MSSIM	Mean structural similarity image measurement
PSF	Point spread function
PSL	Peak side-lobe
PSO	Particle swarm optimisation
ROI	Region of interest
SA	Simulated annealing
SAA	Sparse aperiodic array

SNR	Signal to noise ratio
SPA	Sparse periodic array
SSIM	Structural Similarity Image Measurement
TFM	Total focusing method

LIST OF SYMBOLS

AR_e	Set of emitters array elements
AR_r	Set of receiver array elements
a	Array element width
α	Divergence Angle
BW	Relative bandwidth
β	decreasing temperature rate in the Simulated Annealing
c	Speed of sound
CAN	Signal sets
Crt	Coarray set position
$\vec{C}_{er}$	Coarray element of emitter e and receiver r
$C_{e_1r_1}$	Coarray element of emitter e_1 and receiver r_1
$C_{e_2r_2}$	Coarray element of emitter e_2 and receiver r_2
C_{buf}	Buffer containing the position of the coarray element projected.
D	Diameter of the aperture or Array Size
d	Pitch
dp	Infinitesimal pressure contribution
dx	Infinitesimal distance of the array element
δ	Kronecker delta function
$\delta(t - \tau_{er})$	Time shifted impulse
$\Delta\tau$	Time delay between two elements
$\Delta\theta_{-6dB}$	Main lobe width when the lateral profile decrease to -6dB
$\Delta\theta_{DR}$	Main lobe width is defined at the level of the dynamic range
e	Euler's constant
E	Energy used to create the new FF
e	Index used to indicate emitter elements

$\vec{e}_e$	Vector with the position of the emitter element
$\vec{e}_i$	Vector with the position (x_i, y_i) of the element
$\vec{e}_r$	Vector with the position of the receiver element
η	$\eta = 1.5/(BW f_c)$.
f_c	Center frequency of the array
f_s	Sample Frequency
FP	counter of the filled positions in the MAP matrix
G_c	Candidate to the acquisition set
GFP	Global free positions counter
$GNFP$	Global non-free positions counter
$g(t)$	Ultrasonic pressure pulse
g	Column position of the CPG matrix
$g(t - \tau_{er})$	Ultrasonic pressure pulse delayed
$h(\theta, \theta_s, t)$	Array impulse response in relation to θ and θ_s
$h(u, t)$	Array impulse response in relation to u
$h(\vec{r}, \vec{r_f}, t)$	Impulse response of 2D array
H	Entropy used to create the new FF
$H_1(\theta)$	Radiation Pattern of an array in a given angle θ
$H_2(\theta)$	Radiation Pattern of an element in a given angle θ
$H_2(\theta, \phi)$	Radiation Pattern of an element in a given angle θ and ϕ
i	Variable used as an index
$i0$	Pair of emitter and receiver elements current selected
$I(x, z)$	Image amplitude at pixel x and z
$I(R, \theta)$	Image amplitude at pixel radius R and angle θ
I_1	First ultrasonic image used to calculate the $MSSIM$
I_{1_i}	Area of the image I_{1_i}

I_2	Second ultrasonic image used to calculate the $MSSIM$
I_{2_i}	Area of the image I_{2_i}
j	Imaginary unit ($j^2 = -1$)
L	Array element length
λ	wavelength
k	Wavenumber
k_1	Weights used in the fitness function
k_2	Weights used in the fitness function
N	Number of elements in the array
N_c	Maximum number of parallel channels
N_g	Number of angles where the coarray elements are projected
N_k	Exchange control in the Simulated Annealing algorithm
N_p	Number of coarray grid positions
N_{pix}	Number of pixels in the PSF image
N_s	Number of signals used to create an ultrasonic image
NFP	Counter for the redundancy introduced in the MAP matrix
MAP	Matrix that counts the number of coarray elements that fill a position (p, g)
MPD	Maximum number of Parallel Degree
M_r	Redundancy level
M_o	Occupancy rate
μ	Mean
θ	Azimuth angle
θ_i	Azimuth angle for the array element i
θ_s	Azimuth angle where the beam is steering
P	Location were all acoustic pressures sum
PD	Parallelism Degree per element counter

$P(R, \theta, t)$	Sum of the acoustic pressures
p	Row position of the CPG matrix
$p(\theta, \theta_s, t)$	Acoustic pressure in wide band response
$p(R, t)$	Acoustic pressure in a radius R for a given time t
$p_i(R, \theta, t)$	Acoustic pressure in a radius R_i for a given azimuthal angle θ and time t
$p(\vec{r}, \vec{r_f}, t)$	Acoustic pressure wide band response for 2D arrays
p_0	Function of the wave number k
PSF_{ref}	Reference point spread function
ϕ	Projection angle
ϕ_p	Angular discretization
φ	Phase in the Fermat spiral array
ρ_i	Values of the probability distribution
ρ	Probability distribution used to calculate the Entropy
r	Index used to indicate receiver elements
R	Radius distance
R_i	Distance from the array element i to the point where the acoustic pressure is analysed
R'	Distance from a point in the array element to the point where the acoustic pressure is analysed
RCP	Acquisition Strategy based on reciprocity
R_x	Number of parallel channels
$s_{er}(t)$	Ultrasonic signal related to the emitter e and receiver r
$\hat{s}_{er}$	Hilbert transform of the ultrasonic signal related to the emitter e and receiver r
σ	Standard Deviation
t	Time
T_k	Current temperature used in the Simulated Annealing algorithm

T_x	Number of elements emitting
τ	Time of flight
τ_{er}	Delay time of the ultrasonic wave that propagates from the emitter e, is reflected and reaches the receiver r
$\tau_{er}(x, z)$	Time of flight from the emitter element to the point (x, z) and back to the receiver element
u	$u = \sin(\theta) - \sin(\theta_s)$
u_0	Constant related to the ultrasound pulse transmitted by a single element
x	variable x used to represent any value
x_0	start the solution of a metaheuristic
x_v	best solution of a metaheuristic
y	variable y used to represent any value
w_i	Amplitude Modulation
w_{er}	Amplitude Modulation related to the emitter e and receiver r
ω	Angular frequency
ω_θ	$\omega_\theta = -kd\sin(\theta) + \omega\Delta\tau$

CONTENTS

1 INTRODUCTION

Ultrasonography is a relevant medical procedure used in several areas such as cardiology, orthopedics, and gynaecology. Using ultrasonic images, pathologies are detected in a non-ionizing, non-invasive, and non-traumatic way. It also allows the visualization of abnormalities that are not detected using other techniques, such as the ventricular septal defect, which cannot be diagnosed using the electrocardiogram (DAKKAK; OLIVER, 2020).

Ultrasonic systems are cheaper than other equipaments, such as tomography or magnetic resonators. It allows fast diagnosis and can be used to combat pandemics by earlier identifying a person suffering from an illness, such as the use of lung ultrasound to diagnose the coronavirus (COVID- 19) (DUGGAN et al., 2020; QIAN et al., 2020; YU et al., 2020; BEVAN et al., 2020). It is also used for non-destructive testing to monitor parts and prevent accidents. There are several applications for ultrasound imaging in non-destructive testing to detect defects in parts and structures, such as cracks, delaminations and corrosions, and prevent accidents (LAROCHE et al., 2020; JOLLY et al., 2015; KHALILI; CAWLEY, 2018).

The simplest way to generate an ultrasonic image is to use a single-element transducer, for example, a piezoelectric element that converts electrical energy into acoustic pressure, and vice-versa. The transducer is excited, generating an acoustic wave that interacts with the medium (reflections, refractions, attenuation, etc.), and the same transducer can receive the echoes. By moving the transducer along a line, for example, an image can be created by plotting the reflected amplitudes for each transducer position. An array is a group of piezoelectric elements which can be linearly placed to image a section of an object, or bidimensionally (2D), to create volumetric images. One significant advantage of using arrays is that the individual elements can be independently excited, creating the possibility of beam steering and focusing without the need to move the array (or demanding small movements, in some cases). Although electronic complexity increases, lateral resolution and contrast can be improved compared to single-element operation (DRINKWATER; WILCOX, 2006).

When using an array, a recommendation for the distance between the centre of adjacent elements is at most 0.5λ, where λ is the wavelength (LOCKWOOD et al., 1996a). This distance, called pitch, is relevant because, when the elements have a pitch higher than 0.5λ, the resulting irradiated energy sums in different areas resulting in image deterioration. Another feature that contributes to image quality is the size of an array: the broader an array, the better the lateral resolution of an image (TRUCCO, 1999).

In this sense, the construction recommendation is to use larger arrays with 0.5λ pitch. Nevertheless, extending the size of an array increases the number of elements, and, in consequence, increases the electronic complexity, data volume, and time to generate an image, which might be undesirable for a specific application or even make the imaging system impractical.

The need to find a solution for this problem is clear for 2D arrays, which are used to create volumetric images. Considering an array with $32\lambda \times 32\lambda$ dimension, if the elements are placed in a matrix pattern, 16384 elements would be required. Despite this type of array being physically fabricated using CMOS technology (ORALKAN et al., 2003), the resource to control all these elements turns its use impractical. For example, using the synthetic aperture technique (JENSEN et al., 2006), which is an imaging strategy where the emitter elements of the array are sequentially excited and the sampled ecos stored and post-processed, 268,435,456 mathematical operations would be necessary to create an image pixel, which is time-consuming and impractical for real-time applications.

There are different strategies to enable the use of this array. For example, Karaman et al. (2009) created a method that defines the minimum number of elements in a matrix array, decreasing the time to generate an image. Combining the synthetic aperture technique and their strategy would be required 64,516 mathematical operations to create an image pixel, considerably reducing the number of operations. However, this strategy only works for matrix arrays. For arrays where the elements are not placed in a matrix grid (non-grid arrays), it is necessary to create a different method that selects the emitter and receiver elements of the aperture, which creates a routine that reduces the number of acquisitions required, enabling real-time applications and decreasing the computation cost to generate an image for non-grid arrays.

Another strategy consists in creating a sparse array, in which elements' pitches are higher than 0.5λ. With fewer elements, the area covered is still high and the lateral resolution remains elevated. However, because of the energy summing in different areas, the sparse array has the problem of decreasing the image's contrast compared to an array that respects the 0.5λ recommendation. Although linear arrays uses fewer elements (64 to 256) and is commercially spread, the use of sparse linear arrays might be still beneficial. For example, new imaging systems migth use the power supply and computation power of cellphones to generate images. Sparse arrays could be handy for this application, as fewer elements demand fewer resources (battery, processing). Moreover, if a certain number of elements in a probe burns, a sparse linear array could be designed to work without this array. The burned and some specific elements from the array are excluded from the imaging process, and the resulting image still would have good lateral resolution and contrast. This strategy allows to recycle and extend the array's life.

The need for sparse 2D arrays is straightforward justified when compared to linear arrays because of the higher number of elements and signals involved. At this date, matrix arrays with a reasonable size, as mentioned previously, have an elevated number of elements, becoming impossible to control all of them simultaneously (MARMONIER et al., 2022). Consequently, 2D sparse arrays are practically mandatory to achieve high lateral resolution using a manageable number of elements.

One strategy is to distribute the elements using a nature-based equation, such as the Fermat spiral equation, where the displacement is in a non-grid area. With fewer elements, it is possible to cover a wider area and distribute the elements with reduced periodicity, which is a problem that contributes to increased artefact intensities in ultrasonic images (MARTÍNEZ–GRAULLERA et al., 2010).

Another strategy is to use search engines to design a sparse configuration, where the algorithm determines the elements' position (ROUX et al., 2017). These search algorithms, called metaheuristics, are part of stochastic optimization methods that can intelligently test solutions and return the best-found, according to a predefined condition (NESMACHNOW, 2014). In general, for ultrasonic imaging systems, the search mechanism creates different sparse configurations and finds one that attends to defined circumstances, such as image quality and system resources. Moreover, these two strategies can be merged to create sparse 2D arrays where, at first, the elements are placed in a non-grid distribution. Then, metaheuristics eliminate elements and create a more sparse aperture.

1.1 OBJECTIVE

The main goal of this work is to find strategies to decrease the time, data volume and resources of an ultrasonic imaging system.

1.1.1 Specifc objectives

- Understand how the ultrasonic images are generated and investigate the modelling methods used to evaluate linear and 2D arrays.
- Analyse the different metaheuristics to design sparse linear arrays.
- Propose a technique to design linear sparse arrays.
- Identify and remove redundant information for imaging systems based on synthetic aperture for 2D arrays.
- Define a strategy to design 2D sparse arrays for non-grid apertures.

1.2 OUTLINE OF THE WORK

Chapter 2 gives the theoretical background and the literature review regarding fundamental and state-of-the-art techniques used in this work, where the mathematical functions used to evaluate, types and the strategies used to create sparse arrays are presented. Then, different metaheuristics working to design linear sparse array configurations are analysed, where a new codification and a fitness function based on the simulation of a point reflector are presented in chapter 3. In chapter 4, an acquisition strategy for synthetic aperture is presented where the aim is to decrease the acquisition for non-grid 2D arrays and enable real-time applications. In chapter 5, spatial parameters created during the previous chapter are analysed and used to define a fitness function that is used with the simulated annealing algorithm to design sparse non-grid 2D arrays. Final considerations are made where the contributions of this work are highlighted and future ideas given.

6 FINAL COMMENTS AND FUTURE WORK

6.1 RECAPITULATION AND APPLICATIONS

In this work, different aspects of ultrasonic imaging systems are improved using search techniques. At first, stochastic algorithms found configurations of sparse linear arrays, where a new codification method and the RP FF helped to find configurations with lower FF than those presented in the literature. Afterwards, sparse arrays' analysis enables us to verify that the RP FF has problems distinguishing which sparse arrays would generate high or low-quality images. Considering this problem, a new FF based on the PSF was proposed. This FF was used to find different sparse configurations where it was possible to check that this FF can distinguish how better a sparse array would generate an image based on the reduction of the FF value. Comparing the configurations found using the two FF, the ones based on the PSF balance the lateral resolution and contrast better than the RP FF.

Although the linear array systems already work with hundreds of elements, there are some applications for sparse linear arrays. These arrays require less energy to operate when compared to FPA with the same length. Therefore, an ultrasonic system that works in a region with restricted energy access, such as inside rain forests or in health care in impoverished areas, can use sparse linear arrays to save energy. The system might use a smartphone as a processing core and energy source.

Moreover, the design of sparse linear arrays enables the re-use of ultrasonic transducers with few elements malfunctioning. A sparse array can be designed where the broken elements and others are removed from the imaging system. In consequence, the ultrasonic probe is re-used, helping extend its lifetime. These applications help the health access in developing/poor countries and increase health quality worldwide.

In the second part of the thesis, a heuristic creates acquisition strategies for synthetic aperture systems. The algorithm analyses the projections of the coarray elements that most fill a grid matrix with low redundancy to build an acquisition. Different acquisitions for spiral Fermat and annular segmented arrays were analysed, which overall indicated that signals can be removed from the imaging system without much loss in the image quality.

At last, during the development of the acquisition strategy, two parameters were created to verify the occupancy and redundancy of an array in a grid. These two parameters were studied to check their influence on the radiation pattern response. Understanding its influence, a fitness function was created, and the simulated annealing algorithm was used to create sparse arrays in two setups. First, the elements in a pre-defined spiral array were selected using the algorithm. Then, the metaheuristic selected different radii of a grid to create an annular segmented array. The results of the radiation pattern analysed indicated that the optimized spiral array has better characteristics compared to the spiral where the elements were randomly selected. When compared to the optimized annular segmented array, the radiation pattern of these arrays had better qualities compared to the spiral Fermat array. It was possible to use spatial measurements to evaluate sparse arrays based on non-grid arrays.

2D arrays create volumetric images without the need to sweep the transducer. It is possible to manufacture transducers with thousand of elements using CMUT, and the problem is to handle the data volume, electronic resources and acquisition time required to generate an image. Non-grid apertures have a better spatial element distribution compared to matrix arrays, achieving lower side lobes intensities and high lateral resolution using fewer elements. The acquisition strategy proposed reduces the acquisition time and data volume to generate an image, which enables the creation of real-time ultrasonic applications using the synthetic aperture technique.

The proposed 2D sparse array design method reduces the number of elements used in a pre-defined array. With this element reduction, phased array systems, which are used worldwide, can handle the number of elements in the sparse array. Moreover, the acquisition strategy technique can be used in the sparse array to reduce the resources required to manage the 2D transducer and create a real-time ultrasonic system based on a synthetic aperture technique.

Each part of the work helps to improve ultrasonic imaging systems by reducing the resources involved. In consequence, the data volume, electronic complexity, acquisition time and time to generate images are also reduced, enabling the use of ultrasonic images for different applications.

6.2 CONTRIBUTIONS

The highlights of this thesis are:

- A review in ultrasonic array simulation for linear and bidimensional array and imaging strategies.
- A study in continuous metaheuristics and a codification strategy that helped to find better sparse linear arrays.
- A new FF applied to linear sparse array design that correctly evaluates the arrays.
- A heuristic that builds an acquisition strategy for synthetic aperture for non-grid arrays.
- A study in spatial parameters and how it is linked to the radiation pattern wideband response.
- A optimization strategy to design sparse non-grid for Fermat spiral and annular segmented arrays

6.3 PUBLICATIONS

Journals:

- DE SOUZA, J. C. E.; PARRILLA-ROMERO, M.; HIGUTI, R. T.; MARTÍNEZ-GRAULLERA, O. Design of Ultrasonic Synthetic Aperture Imaging Systems Based on a Non-Grid 2D Sparse Array. **sensors**, v. 21, n. 23, p. 1-20, 2021.
- MARTÍNEZ-GRAULLERA, O; DE SOUZA, J. C. E; PARRILLA-ROMERO, M. ; HIGUTI, R. T. Design of 2D Planar Sparse Binned Arrays Based on the Coarray Analysis. **sensors**, v. 21, n. 23, p.1-21, 2021.

Congress:

- DE SOUZA, J. C. E.; PRADO, V. T.; MARTÍNEZ-GRAULLERA, O.; HIGUTI, R. T. A New Fitness Function for Sparse Linear Array Evaluation Based on the Point Spread Function. In: IEEE UFFC LATIN AMERICA ULTRASONICS SYMPOSIUM, 2021, Gainesville. **Anais...**, Gainesville: IEEE, 2021. p. 1–4.
- MARTÍNEZ-GRAULLERA, O.; DE SOUZA, J. C. E.; HIGUTI, R. T.; ROMERO, M. P.; RODRIGUEZ, A. I. Técnica De Conformación Basada En El Coarray Para Mejorar La Calidad De Imagen En Sistemas De Apertura Sintética. In: XI CONGRESSO IBÉRICO DE ACÚSTICA E 51º CONGRESO ESPAÑOL DE ACÚSTICA,2020, Faro **Anais...**, Lisboa: Sociedade Portuguesa de Acústica (SPA), 2020. p. 789-800.
- MARTÍNEZ-GRAULLERA, O.; DE SOUZA, J. C. E.; HIGUTI, R. T.; ROMERO, M. P.; RODRIGUEZ, A. I. Prototipo De Un Array Bidimensional Ultra-disperso Para Imagen Ultrasonica De Alta Resolucion. In: XI CONGRESSO IBÉRICO DE ACÚSTICA E 51º CONGRESO ESPAÑOL DE ACÚSTICA,2020, Faro **Anais...**, Lisboa: Sociedade Portuguesa de Acústica (SPA), 2020. p. 777-788.

6.4 FUTURE WORKS

Non-grid arrays can be designed using the linear sparse array optimization algorithm presented in Chapter 3. This increase in the degree of freedom might contribute to the quality of the sparse linear array image, especially related to sidelobes reduction. The designed 2D arrays should be experimentally tested, but there are practical difficulties related to array manufacturing and costs. Another possible application is in the inspection of plate-like structures using Lamb waves, where the elements do not necessarily need to be placed in a linear fashion but can be distributed along the plate surface. Another idea is to use the acquisition strategy proposed in Chapter 4 in the optimized apertures found in Chapter 5 to reduce even more resources. At last, the design of 2D apertures can be enhanced by considering the optimization of the phase in the annular segmented array.

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